

The Transmission of Cathode Rays through Matter.

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Introduction.

The bare fact that cathode rays lose velocity on passing through matter has been known for some time. Leithauser,* who discovered that the loss of speed was much greater for slow than for fast rays, made no attempt to discover a law of transmission. It is interesting to notice that the parallel effect in the case of β -rays is so small that for some time it defied detection;† its existence, however, has now been definitely proved, and quite recently has been investigated by W. Wilson‡ in as careful and detailed a way as at present seems possible. Wilson found that owing to the limitations of his apparatus he was unable to take measurements accurate enough to distinguish between relations of the type

$$v_0^4 - v_x^4 = ax \quad (1) \quad \text{and} \quad v_0^2 - v_x^2 = ax, \quad (2)$$

where v_0 is the velocity of the rays incident on an absorbent sheet of thickness x , v_x is the greatest velocity possessed by the transmitted rays, and a is some constant depending on the absorbing material.

Since in these experiments with β -rays the initial velocities (v_0) only ranged between 2.85 and 2.48×10^{10} cm./sec., it is, perhaps, hardly surprising that the results should be difficult of exact interpretation. In the case of cathode rays it is easy to produce rays comprised in a wide range, since the difficulties presenting themselves are mainly ones of manipulation, which can usually be surmounted.

The Apparatus.

The form of the apparatus is indicated in fig. 1.

Heterogeneous cathode rays from the cathode E suffer magnetic dispersion in the solenoid B; a definite velocity corresponding to deflection through a right angle is allowed to enter D and to traverse a thin metal sheet contained therein. The transmitted rays enter the second solenoid C and again suffer magnetic dispersion, and so have their velocity measured. In

* Leithauser, 'Ann. d. Phys.,' vol. 15, p. 283.

† Schmidt, 'Phys. Zeit.,' 1907, vol. 8, p. 361.

‡ W. Wilson, 'Roy. Soc. Proc.,' A, vol. 84, p. 150.

this way relations can be obtained connecting the velocities of the incident and emergent rays and the thickness of the absorbing material. Some details of manipulation will now be given, but for a fuller account of the construction and use of the solenoids reference must be made to previous papers.*

A is a spherical discharge tube cemented as shown to the brass, solenoid-wound cylinder B. The cylinders B and C are vacuum-tight and exactly similar, being 35 cm. long, 10 cm. in diameter, and similarly wound on the

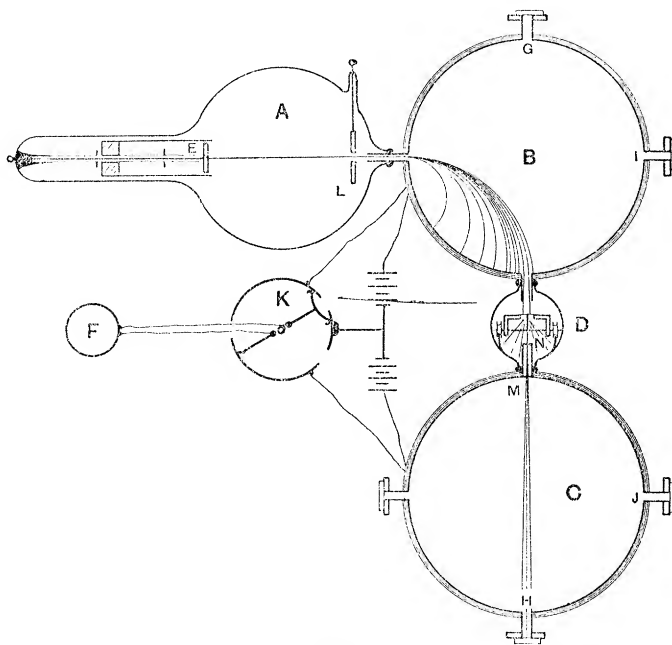


FIG. 1.

outside with insulated copper wire, through which currents up to 10 ampères can be passed. Four narrow brass tubes a few centimetres long pierce each cylinder; neighbouring tubes are at right angles, and the plane in which they lie bisects the axis of the solenoid at right angles. The two solenoids are arranged for convenience with their axes parallel. The glass tube D which connects B and C is about 3 cm. in diameter and 30 cm. long. It is provided with two side tubes fused in as shown, and placed at the centre of the length of the tube. D contains a magnetically controlled trolley of a kind already described,[†] carrying a number of metal sheets fixed horizontally

* Whiddington, 'Camb. Phil. Soc. Proc.,' 1911, vol. 16, Part II, p. 150; 'Roy. Soc. Proc.,' 1911, A, vol. 85, p. 325.

† Whiddington, 'Roy. Soc. Proc.,' 1911, A, vol. 85, p. 101.

to a suitable framework. Just below this trolley and fitting closely into the upper tube of the lower solenoid there is a brass tube 5 cm. long, carrying at its ends narrow parallel slits M and N about 0.06 cm. in width. These slits are arranged so as to be parallel to the axes of the solenoids. They are essential because the cathode rays which strike the leaf perpendicularly on its upper surface are completely scattered during transmission so as to move in all directions on emergence from the lower surface, so that it becomes necessary to limit the beam entering C to a very narrow cone.

The interiors of the cylinders are painted with a water emulsion of Willemite, so that the places struck by the rays can be visually observed.

There are two very important adjustments to be made which require some explanation. Firstly, the central axes of the tubes G and H and the centres of the slits M and N must all lie in one straight line, and, secondly, the central normal to the cathode E must pass centrally down the tube I. The second adjustment fulfils the condition for the rays from E (when no current passes round either solenoid) to envelop that diameter of the solenoid B which is at right angles to the diameter HM of the solenoid C. The first adjustment ensures that those rays which have been deflected magnetically through a right angle in B so as to enter and traverse the tube D envelop a diameter of C (this is the state of affairs represented in fig. 1).

Both these adjustments are most easily made by an optical method. A small electric glow lamp is mounted in a brass tube so as to be nearly at the focus of a convex lens, an arrangement giving a sufficiently powerful beam of light for the purpose.*

The first adjustment is made by clamping this collimating system vertically above G so that its axis is parallel to the vertical diameter of B. This will be effected when a uniform circular halo of light surrounds the opening connecting B and D. By gently warming the joints between B, C and D, the cement can be softened enough to allow of slight movements of C and D until the beam of light passes down H. The adjustment is then complete, and the cement is allowed to set in that position. The second adjustment is somewhat easier to make. The collimating system is clamped horizontally opposite I so as to send a beam of light along the horizontal diameter of B, and A is then adjusted until a circular spot of light appears in the centre of the cathode. This means that the centres of E, the aperture in L, and I are in alignment, but it does not mean that the plane of the cathode is perpendicular to this line. This is assured by making the light reflected from the polished surface of E uniformly illuminate the edge of the circular hole in L.

There still remain a few practical details in connection with the measure-

* It is best to use a slightly diverging beam.

ment of the currents in the solenoids, to which attention must be drawn. The currents required are obtained from two exactly similar sets of "motor cells" connected in opposition as indicated in the figure, the controlling resistance frames not being shown. The specially designed two-way key K makes it possible for the currents in B and in C to be measured by the same ammeter F; in one position of the key the current in B passes through F while that in C passes through a short copper strip, while in the other position the current in C passes through F while that in B passes through the strip. Since the resistances of both ammeter and strip are small in comparison with the resistance of a solenoid, the magnitude of the currents passing is independent of the position of the key—a fact experimentally verified with the help of a second ammeter placed in one or other of the two circuits.

As has been pointed out in a previous paper (*loc. cit.*) a solenoid so short as the ones here used, while largely concentrating the field within itself, sets up a small, but appreciable external field. Such a field can be balanced out at any desired point by means of a suitably placed coil of wire in series with the solenoid. Such a compensating coil does its work whatever the value of the solenoid current, since the external field is always a definite fraction of the internal field, which is itself proportional to the exciting current.

In this particular experiment a rather complicated system of compensating coils is necessary, since there are two solenoids and four places where their external effects have to be eliminated. There are the joint effects of B and C at A and at D, and there are the separate effects of B within C and of C within B. The requisite compensating coils assume rather unwieldy shapes, but prove very satisfactory after having once been set up. They were adjusted with the help of a small compass needle, the compensation being sufficiently complete when, with the greatest current likely to be used passing round the solenoids, the oscillations at the required place were very slow. The effect of the earth's field is in any case very small, and is practically eliminated by arranging for the axes of the solenoids to point east and west.

The apparatus has now been sufficiently described. The current (c_0) in the solenoid B is proportional to the velocity (v_0) of the cathode rays striking an absorbing sheet in D, so that

$$v_0 = Gc_0.$$

Also, if c_x is the current required to deflect the transmitted rays through a right angle in C so as to pass down J, their velocity v_x is given by

$$v_x = Gc_x,$$

the value of the constant G being accurately known.

It is of some interest to compare the dimensions of the apparatus here used with those of the β -ray apparatus employed by Crowther* and by W. Wilson.† It is clear that experiments of far greater accuracy can be performed with cathode rays.

	β -rays.	Cathode rays.
Slit width	1 cm.	0.06 cm.
Radius of path of rays	3.5 „	10 „

A really formidable difficulty arises from the fact that cathode rays of the moderate velocity which can be dealt with in this apparatus lose their speed very rapidly in passing through solids. It is necessary on this account to make use of very thin absorbing sheets. The only metals which can be beaten out into leaf appear to be Al, Au, Ag, Cu, Pt, Sn. Of these six metals only Al and Au prove to be suitable for quantitative work, since the others are either too thick or not sufficiently uniform in thickness. It is very necessary to use uniform leaf, because the rays traverse the leaf at one particular point, and the thickness of the material at that point must be taken to be the same as the average thickness of the whole leaf, obtained from a knowledge of its weight and area. The books of leaf as supplied by the beaters contain leaves of extraordinarily equal weights per unit of area, indicating a very good *average* uniformity, yet the individual leaves frequently show considerable local departure from uniformity. It is a *general* uniformity which is so essential and which can only be attained, apparently, in the case of Al and of Au. Unfortunately, both Al and Au are peculiarly liable to rupture under the action of the cathode rays, so that the experiments have to be carried through as quickly as possible. Cu leaf is very much tougher and is accordingly used in any experiments where the actual thickness of the absorbing screen does not require to be known.

Experimental Results.

When there is no absorbing sheet in the path of the rays as they traverse D, magnetic deflection in C produces a sharply defined line of phosphorescence of the same width as the original undeflected one. Moreover, the current in C required to bend round the spot to J has exactly the same value as that in B, showing that the compensating coils are properly adjusted. The interposition of a thin metal sheet in the path of the rays as they pass through D altogether alters the appearance of the deflected beam in C. The single line of phosphorescence is now replaced by a long band or spectrum with a well marked maximum at the extreme high velocity end.

* Crowther, 'Proc. Camb. Phil. Soc.,' vol. 15, Part V, found himself able to reduce the slit width to 0.5 cm. with a path radius 4 cm.

† *Loc. cit.*

and gradually tailing off towards the low velocity end. Also the current in C required to cause this maximum to fall on J is perceptibly less than the current passing through B. It is the velocity of the rays comprising this maximum with which the present investigation is concerned.

The following table gives some results obtained by allowing rays of different velocities to fall on a single sheet of Cu. This metal is used for the reason given above, since this particular experiment does not require a knowledge of the thickness of the absorbing material. The first column gives the various values of v_o , the velocity of incident rays, the values of v_x , the velocity of the resulting transmitted beam, appearing in the second column. The third column shows that $(v_o^4 - v_x^4)$ is very nearly constant.

Table I.

$v_o \times 10^{-9}$.	$v_x \times 10^{-9}$.	$(v_o^4 - v_x^4) \times 10^{-38}$.
5·31	4·59	3·51
6·12	5·72	3·33
6·94	6·66	3·50
7·76	7·53	3·80
8·58	8·45	3·20

The values of v_x given in the above table are each the mean of several observations differing amongst themselves by not more than 1 or 2 per cent.

The next table shows how the velocity diminution depends on the thickness of material traversed. The rays in this experiment were caused to pass through piles of Au leaf of different total thicknesses ranging from one to five leaves, the thickness of each leaf being about 0·00001 cm.

Table II.

Number of leaves traversed (n).	$(c_o^4 - c_x^4)$.	$(c_o^4 - c_x^4)/n$.
1	13·9	13·9
2	30·4	15·2
3	42·2	14·1
5	69·0*	13·8

* This observation can hardly be expected to be of much worth, since 5 gold leaves diminish the *number* of the rays to such an extent as to make it very difficult for the eye even to *see* the transmitted spectrum.

In this table it has not been thought necessary to convert solenoid currents to velocities, so that the second column gives numbers proportional to $(v_o^4 - v_x^4)$; c_o and c_x are the actual solenoid currents, c_o being kept constant throughout the experiment. It is clear that the numbers in the second column are proportional to those in the same line of the first column, from which it follows that the relation (1)

$$v_o^4 - v_x^4 = ax$$

is obeyed.*

* A relation deduced theoretically by Sir J. J. Thomson some years ago. See 'Conduction Through Gases,' 2nd Edition, p. 378.

The law has been tested also for Al and appears to be pretty accurately true; there seems indeed every reason to suppose that the relation is true over quite a wide range of velocities, a point which will be returned to very shortly.

The constant a has been measured as accurately as possible for the metals Al and Au, and comes out to 7.32×10^{42} and 2.54×10^{43} respectively.

Thus from (1) it appears that the maximum in the transmitted spectrum of cathode rays of initial velocity v_0 , after passing through x cm. of Al, contains rays of velocity

$$v_x = (v_0^4 - 7.32 \times 10^{42} \times x)^{\frac{1}{4}}, \quad (3)$$

a formula which will be found later to be of great practical utility.

It is interesting to see whether (1) will bear extension to faster negative particles such as the β -rays used by W. Wilson. In the experiments of this investigator the β -rays from a sample of radium were passed through 0.0245 cm. of Al, their velocity being measured before and after transmission in much the same way as in the present investigation. In Table III some of Wilson's results are compared with the values resulting from an application of (3). The values of the velocities are in every case multiplied by 10^{-10} .

Table III.

v_0 .	v_x (observed by Wilson).	v_x (calculated from (3)).
2.565	2.25	2.24
2.735	2.68	2.48
2.818	2.77	2.59

It would appear then that the formula (3) holds so long as the rays move with a speed less than about 2.5×10^{10} cm./sec.

This is a rather unexpected result, for the velocity loss during transmission must depend in some way on the mass of the transmitted particles, which at a speed of 2.5×10^{10} cm./sec. has increased by about 50 per cent.

The Transmission of Cathode Rays through Air.

There seems no reason to suppose that the transmission law already proved to be true for metal absorbing sheets should not hold also when the absorbing medium is a gas. It is of particular importance to know the value of the constant a in the case of air, for reasons which will be fully apparent in the next paper, which deals with secondary cathode rays. From the nature of the case it is impossible to use the same method as has been employed in the case of metals, since we cannot compress a given mass of gas into a thin film *in vacuo*. The method which has to be fallen back on is a distinctly inferior

one, and cannot give very accurate results; its adoption is the result of necessity.

Broadly speaking, the method consists in causing a stream of cathode rays of known initial velocity to traverse air at a known pressure. The rays gradually lose their speed and eventually become reduced to comparative rest. When this happens, v_x in the formula (1) becomes zero, and we have

$$a = v_0^4/d, \quad (4)^*$$

in which d is the value of x for which v_x is zero. In the apparatus now to be described d cannot be measured with any great accuracy, so that only an approximate value can be assigned to a .

Cathode rays produced within a discharge tube were first led out into the open air successfully by Lenard, who observed that after escaping through a thin aluminium window, they were able to penetrate several millimetres of air at ordinary pressures. Lenard observed the range of his rays in air by making use of the fact that their track was luminous; in the apparatus indicated in fig. 2, the range of the rays is deduced from the ionisation they

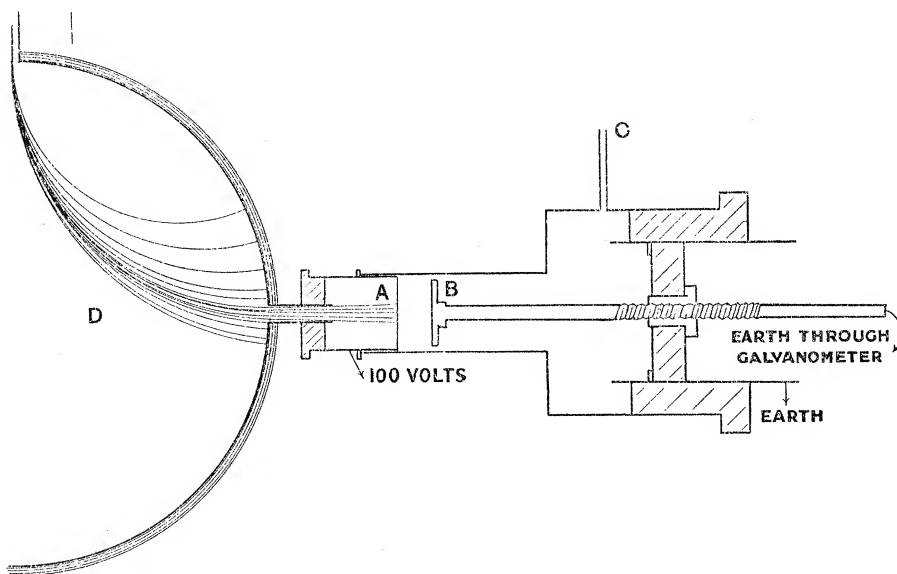


FIG. 2.

produce. It is assumed that a cathode particle may be regarded as having been reduced to rest when it has lost the power of ionising, an assumption perfectly legitimate for the present purpose.

* This formula is more fully discussed in the next paper.

The apparatus consists essentially of a small ionisation chamber of brass about 2 cm. in diameter containing a small circular plane electrode B, placed parallel to and at a known distance from a flat plate A pierced with a number of small holes, each about $\frac{1}{2}$ mm. in diameter. A very thin but vacuum-tight Al leaf is cemented over A. The chamber is connected at C to a mercury manometer, drying tubes, and a Fleuss pump, so that the space between A and B can be filled with dry air at known pressures. Homogeneous cathode rays of known velocity are directed on to that side of the window remote from B by means of a discharge tube and solenoid D of the type used in the previous part of this investigation. By suitably adjusting the speed of the rays falling on A, the ionisation produced within the chamber can be made sufficiently intense to measure with a galvanometer. The outside of the chamber and A were charged to a potential of 100 volts, while the collecting electrode B was connected to earth through the galvanometer. From a knowledge of the thickness of the window and the velocity of the incident beam, the velocity of the speediest rays entering the ionisation chamber can be calculated from (3). It is clear that it is this maximum speed which determines d in (4). The apparatus shown in the figure is capable of being used in two distinct ways. We can either alter the distance x between the plates and note when further increase of x at constant pressure produces no increase in ionisation, or we can keep the distance between the plates constant and determine the lowest pressure necessary to yield the greatest possible ionisation. The latter method was adopted on account of its greater simplicity.

If p is this pressure above which the ionisation is independent of the pressure and P is the normal atmospheric pressure, then

$$d = bp/P,$$

where b is the actual distance between the plates.

Unfortunately, it is impossible to construct really satisfactory pressure-ionisation curves (as Beatty has done, using secondary cathode rays) from which to determine p with accuracy, the reason being that it is not possible to keep everything steady long enough to go over the whole curve.

The method finally adopted was to start with the pressure high enough to completely absorb the rays and then to exhaust the chamber very gradually. The galvanometer deflection remains constant until the pressure p is reached, when it commences to diminish. By taking the mean of a number of observations a probable value for p can be arrived at. It is very important to work with the rays as fast as possible, since p is then as large as possible, and consequently errors in observation are of the least possible account.

This method, however, is almost certain to give too low a value for p , and consequently too small a value for d . Thus the value of a deduced from (4) is, from this cause, at any rate, in all probability too large.

There is one rather curious experimental difficulty which deserves particular mention.

When the pressure on the thin Al windows is that due to the atmosphere, the leaf (which, by weighing, is only 0.000432 cm. thick) takes up a permanent concave form. The distance between A and B thereby increases, and not only so, but the thickness of the windows must be diminished, because the material has been permanently stretched to a larger area. The central elements of the windows appear to be depressed about 1/10 mm. below the general level of A, a rough estimate, arrived at by focussing on the window with a high-power travelling microscope. The distance b was therefore taken to be 0.41 cm. instead of 0.40 cm.; there is room here, of course, for some error. Now, it is very important to know the thickness of the windows, because it enters into the expression (3) from which the velocity of the rays entering the ionisation chamber is calculated. We can form an approximate estimate of the diminished thickness of the windows by assuming their sagged form to be spherical and calculating their new areas. If this is done, then it comes out that they are reduced in thickness from 0.000432 to 0.000348 cm.

Now it follows from (3) that unless $v_0^4 > 7.34 \times 10^{42} \times x$ no rays can penetrate the window.

This affords an entirely different and, perhaps, more satisfactory method of determining the thickness of these little windows. It is merely necessary to increase the velocity (v_0) of the rays until they are just able to penetrate through to the ionisation chamber. This was found quite easy to do, since, on account of the low speed of rays to be used, the apparatus gave very steady readings. A curve was drawn connecting the ionisation between A and B with the velocity of the incident cathode stream. The curve bent very sharply upwards at a certain velocity, this value is the proper one to substitute in the relation

$$x = v_0^4 / 7.32 \times 10^{42}.$$

Found in this way, x comes out to 0.000340 cm., a value in very close agreement with that found above from geometrical considerations (viz., 0.000348 cm.).

The value 0.000340 cm. for the thickness of the window is used in calculating a , the mean value of which comes out to be

$$2.0 \times 10^{40}.$$

Unless there are unsuspected sources of error, this value of a for air should not be more than 15 per cent. from the true value.

Summary.

It has been found experimentally that a cathode ray moving with velocity v_0 can possess, after traversing a thickness x of material, a velocity v_x given by the relation

$$v_0^4 - v_x^4 = ax,$$

where a is a constant depending on the nature of the material.

This constant a has been measured for Al, Au, and air at 760 mm. pressure of mercury and 15° C., with the following results :—

Al	7.32×10^{42}
Au	2.54×10^{43}
Air	2.0×10^{40}

There seems to be no simple law connecting the value of a with the density or atomic weight of the absorbing material.

The Velocity of the Secondary Cathode Particles Ejected by the Characteristic Röntgen Rays.

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Introduction.

When a metal plate is “illuminated” by Röntgen rays, part of the energy of these incident rays is converted into high-speed secondary cathode particles, which are ejected from the plate in all directions. The mere detection of this emission of negative electricity is an easy matter, since the illuminated plate, if insulated *in vacuo*, charges up positively. By measuring the rate of charging, it would be possible to determine the number of particles ejected per second, while by applying an electric force of such a magnitude and in such a direction as to stop the emission, it might be thought that their speed could be measured. In practice, however, this method of measuring velocities is restricted to slowly moving rays, such as are produced, for example, by ultra-violet light. The particles ejected by